Economic Operation and Control of Power System

Prof Narayana Prasad Padhy

Department of Electrical Engineering

Director MNIT Jaipur and Professor IIT Roorkee

Week - 01

Lecture - 01

A very good morning. Welcome you all to the NPTEL course on Economic Operation and Control of Power System. This lecture 1 on Introduction part. Now, if you go through the objective of this course, the main objectives are make all the student familiarize with the power generating systems and their economic operation as well as control. We will also try to introduce the concept of power system optimization and the key application over practical operating problems of a real power network or a power system. We will also try to discuss on different solution processes of the problem, which includes both the economic, and network security aspects. At the end, we will talk about different modern power system control techniques. Now, looking into this diagram, you can see that there are three major components. One is your generating stations, transmission systems and finally, the distribution systems. Now, the generating station ideally the power is being generated through different concept of generating stations either at 11 kV or 33 kV, but enhance to reduce the losses, we step up those voltage, power available to me to a higher voltage level to carry the power generated by your generating station through a transmission line with different voltage ratings. And you can see the voltage rating of those transmission lines is higher 765 kV, 500 kV, 400 kV, 200 kV and so and so, but depending upon the geography of the globe, the transmission line voltage levels are quite different. And hence, we get into the substation step-down transformers where those high voltages have been stepped down and they are made available to my customers of three different types. One is sub transmission customers, primary customers and secondary customers. So, ideally the sub transmission customers are almost industrial customers at 33 kV and the primary customers are small scale industry or large buildings or academic campuses at 11 kV. And then we have secondary customers like we residentials operated 220 V and in North America could be 110 to 120 V. If you look into the schematic diagram of a power system, initially we do have large generators, they could be either thermal, hydro, nuclear and then we allow this power to flow across a transmission line and then we have different type of renewable generations. They are normally integrated at a voltage level, which is below 132 kV, and then we have different type of renewable power plants, especially solar, they are integrated at 11 kV and if they are very large power parks or solar parks, then they can also be integrated at 33 kV. And then the

energy actually flow to customers, we can have residents of rooftop where extremely low voltage distribution system can also accommodate the solar rooftop power plants. And then the energy can flow to large customers, medium customers as well as small customers. Now, the interesting part I like to highlight here, the extreme right component as you could see. So, this area as you could see the low voltage transmission, especially the small consumers, it may so happen that those consumers not only consume energy, but they also do generate energy through their rooftop small scale solar or maybe small wind also. So, that case those consumers sometimes not only purely consumers that they may be treated as the prosumers because they produce power as well as they consume power. And it is very interesting part, you know, if you this kind of integration of energy sources at different voltage levels not only enhance the efficiency of the network, but also it significantly reduces the transmission and distribution losses because the generating station in the past used to be almost very far away 100 to 500 miles away, but today all the generating stations partially available to you next door, so that the transmission and distribution losses are significantly reduced. So, we can note down one point here dear students that because of the renewable integration to distribution and transmission system, this is not going to enhance the energy capability of any power system, but also it may reduce the distribution and transmission losses in a long run. Now, moving next we can see different types of power plants. The first one is thermal power plant you could see very polluted and lot of black gas and then you have hydro power plant which is clean and really good a beautiful one. Nuclear power plant certainly an acceptable one, but excluding bit of security and technology related issues to India and many developing nations and pumped hydro power plant is a very good clean power plant as well as it act as a storage device to us. So, to me pumped hydro power plant must be explored as much as possible across the globe and to come to the last point which is the renewable energy sources, they could be solar and wind as I already discussed. We will talk very much in detail when you proceed further, but at this point of time these are the major five different type of energy sources those are being utilized depending upon the availability of sources across the world. Now, if you focus on power generation in India which is a very interesting story, thermal power generation considered to be or thermal generation contribute the maximum percentage of energy requirement of this nation, but over a period of time there is no growth on thermal generations. So, probably the percentages keep on reducing. Now, if you also see the goal of India and other countries in the world is to reduce the carbon footprints after pledge from the Paris agreement on 3rd August 2022. Now, if you see the current install capacity we do have almost 48 that is close to 50 giga watt of solar and 40 giga watt of wind and 5 giga watt of small hydro and approximately 45 giga watt of large hydro and 10 giga watt of bio power and close to 7 giga watt of, but we do have a large goal set for India considering the aspiration from middle class Indians going to consume more energy in next 10 to 20 years to come. So, India has a goal of 500 giga watt of renewable installation by 2030. It is crucial to

determine how much renewable can be penetrated into the system.

Now, fortunately country like ours where all by power grids or networks are extremely hungry to receive energy because the loads are very very high. So, we do have consumers who can consume and hence I have no problem in accepting or integrating the new renewable or new energy sources to my grid. So, to me Indian power grid is quite fortunate and will certainly be a stable grid for next 10 to 20 years time until unless my available generation is much more higher than my goal. So, till that time certainly we can integrate more renewable, but considering the zonal challenges or geographical challenges in each and every zone it is not necessary that my load is always higher than the generation. In some of the cases especially hydro rich or renewable rich zones where in the desert as well as hilly stations where the consumers are very very less.

So, that case it is a challenge for us to understand how much renewable can further be integrated because the generation is already higher compared to loads in that particular region. So, Indian government is now very keen to create a green corridor where all the renewable energy being generated being properly observed by the grid to make sure that none of the renewable power is curtailed or can go waste at any given point of time. Now, if you look into the thermal power plant boiler turbine generating it is a very simple diagram as you could see that we do have boiler. Through boiler actually there is a input to the generator that is steam turbines and once you generate. So, you get net power and some of the energy produced by the generator can also be used for its own application that is your auxiliary power systems. Now, when you talk about a characteristic of a steam unit which is very interesting because we need to understand what is the input to my power plant and what is my output. So, we are very keen to understand the input output characteristic of a thermal power plant or a steam unit. So, as you know the steam turbine units required close to 2 to 6 percent of gross output for the auxiliary power requirement. So, if you generate 100 percent then probably 98 to 94 percent is available to me and rest is being utilized for driving your boiler, fans, condenser, water pumps etcetera. Now, when you talk about the unit characteristic you can draw a characteristic where the power versus the input in the form of rupees or in the form of tons of coals per hour can be plotted and we can see the characteristic of a thermal power plant by plotting the input characteristic versus the output characteristic. So, what is our input here? Input could be the coal, could be the water and in the form of rupees or in the form of tons and the output is always in the form of megawatt or kilowatt. Now, if you draw the characteristic as we discussed earlier you can see the y axis which represent the rupees per hour, the amount of money being spent per hour to generate power and the x axis shows the power output of the plant. Now, my emphasis here is to highlight those two important points. One is about my P min and the other one is actually P max. So, when we say the power output is P, why there is a P min or P max? What is P min? P min

means the minimum power that is expected to be produced from a power plant at any given point of time means I cannot generate anything less than P min.

Similarly, for a given power plant with its maximum operating point we can generate the maximum power. So, at no time I can go beyond the P max and why those limits are probably when we try to understand the characteristic PQ characteristic of the power plant we will try to understand because for any power plant the rating of the power plant is based on the MVA rating or the KVA rating. So, what is MVA rating? If you see a transformer or if you see a generator the ratings are not in megawatt or kilowatt the ratings are in mega volt ampere or kilovolt ampere means the volt ampere rating is responsible based on the real and reactive power. So, depending upon the reactive power requirement or the reactive power being generated that restrict my actually real power output at given point of time if I say that my machine is rated with 100 KVA and my reactive power generated is 10 KVAR then from those two volt ampere and KVA I can calculate my kilowatt and hence the P generated cannot be 100 watt for a 100 volt ampere machine because there must be some reactive power at all given point of time. So, similarly when you start a generator by the time it starts it cannot be at 0 point because the moment you switch it on. So, it need a minimum amount of power to accelerate its turbine accelerate its power output. So, then hence P minimum and P maximum are the two important variables for a generating plant to decides its operating range between P min and P max. That means, we can operate only between P minimum and P maximum for any practical applications. Theoretically I can say I can go from 0 to 100. So, this is my 0 for example, and this is my 100 watt. Theoretically it is fine, but practically it will be from actually 20 watt to 100 watt or 20 kilowatt to 100 kilowatt or maybe 20 megawatt to 100 megawatt. So, moving to the next one there is an interesting term known as incremental heat rate characteristic. What is incremental heat rate characteristic? It means to generate 1 unit of power how much input need to vary. So, if you see the y axis which very clearly talks about delta H upon delta P that is the derivative of the H with respect to P and the x axis is certainly my P minimum P maximum. So, indirectly it is a derivation of that characteristic. If that characteristic is second order for example,

$$AP^2 + BP + C$$

On differentiating, we get: $2AP + B$

So, you could see this is a very linear type of characteristic that you see in case of your incremental characteristic. This is nothing but the Btu per kilowatt hour that is dollar or rupees per kilowatt hour versus the net power unit in megawatt. It can also be represented as multiplication of incremental heat rate in British turn unit per kilowatt-hour by the equivalent fuel cost in terms of rupees or dollar per kilowatt-hour.

Now, this is one of the practical characteristics where you can see how the P is keep on

varying based on the incremental heat rate and typically for a thermal power plant the efficiency is not very high as it is expected to be. Now, if you look into a multiple channelized steam turbines or steam unit characteristics. Now, what happens you look into the characteristics ok. Now, the characteristic which is keep on changing that is my linear characteristic and the linear characteristic which further actually jumps to another level hence jumps to another level and hence jump to another level. The reason of this oscillation or the variation at different point of zone 1, 2, 3, 4 probably there is a chain of valves that operate at different time intervals ok. So, for large steam turbine generators the input output characteristic is not that smooth as we have shown you earlier. There are many steam admission valves that are open in sequence to obtain ever increasing outputs Now, the outputs for an example if the power plant rating is 100 watt and if you are generating 20 watt or 30 watts it is not necessary to open all the valves at a time. So, based on my requirement as I progress to generate up to maximum slowly I keep on releasing one after other valves to optimally utilize my steams and that perhaps actually disturbs my characteristic which is not very smooth and you can see there is some small oscillation. And that through an important challenge to researchers especially if you are thinking of solving this problem as an optimization. Now, this characteristic is not purely I mean convex and it is absolutely non-convex. So, the classical optimization techniques are not suitable and hence we have to reinvent a new mechanism to obtain the optimal point between P min to P maximum for solving the optimal power output of the given power plant. But now if you see different steam turbines characteristic if you drop the incremental characteristic now you can see it is not only disturbing, but it is altogether a different characteristic. So, it is not linear and you can see that there is a small jump further reduced further reduced and further reduced. So, the incremental characteristic of a steam turbine with multiple valve is too complicated compared to a single valve systems. One more interesting point some of the power plants are also known as co-generation power plants I am very sure that if you are doing your third or final year of undergraduates or if you are a master of PhD student you must be knowing it, but let us revise this concept of co-generation power plant which is very important.

Now, what happens exactly not only country like India, but especially the North America or European joints where we need actually steam to survive because the temperature is too low. So, even in India we use heaters to survive during extreme winter am I right. So, what has happened we generate electricity and that electricity is being generated from heat and then we use that output of power plant electricity as an input to a device to produce heat for the for our survival. So, heat to electricity, electricity to heat will reduce or increase my loss or the efficiency got reduced significantly because if input output of heat to electricity is 70 percent and electricity to heat is 80 percent. So, then the power plant is operating complete system is operating with 60 percent close to 60 percent even below that. So, what we can do if you need steam for your survival and you also need

electricity then we can assign some of the power plant not only focus on electricity generation, but part of the steam can directly be taken out of the power plant for residential use or industries and the plants those are focused not only generating electricity, but also responsible for steam generation those power plants are known as co-generation power plants. Co-generation is referred to a plant that produce both the electricity and the steam. They are similar to the common header plants and many residential and industrial plants such as refineries, chemical plants need steam frequently. So, instead of converting their electricity into steam probably they can buy steam directly from the power plant which is nearly near situated quite near. So, that you know we can use the steam directly instead of getting electricity. And also the need for heat generation unit can be avoided. The overall efficiency of the plant is certainly improved because the second level conversion from electricity to heat is completely omitted. Now, let us move to hydroelectric power plants after thermal generation cost characteristic. Let us focus on hydro power plant. The hydro power plant characteristics are almost similar, but they are not too non-linear I mean they are almost linear characteristics.

So, you can see the input is anyway it is water, water means it is basically the volume of water. So, acre feet is my volume per hour being discharged through the hydro power plant to produce x mega watt of power. So, this is the characteristic where the inputs are my cubic volume of water and the output is my power generator. Now, you can also plot the incremental water rate.

So, you have to differentiate: $\frac{dQ}{dP}$

The previous characteristic we get: $AP + B$

After differentiation is purely A, the constant acre feet per kilowatt hour.

So, you could see the characteristic between P_{min} to P_{max} is perfectly you know linear or the constant to me. Now, moving to nuclear power plants as everyone knows it that uranium based or different type of materials have been used for power generation excluding the security reason. I personally do not see any difficulties in deploying nuclear technologies, but because of security reason we have to think wise and the second problem the technology is not available to everyone. So, it is limited to few tall or I can say a developed nations and hence, by the time you are a developing country having nuclear power generation become a challenge. Similarly, we can also have different type of materials for energy productions and each one of the technology do have merits and demerits, but our responsibility is not getting into details of that, but please try to understand the operation of nuclear power plant is similar to a thermal power plant. So, with this note what I like to say there are many demerits and challenges as I told you because of fabrication technology and safety and the water availability near to the power plant become a challenge. Now, this is one interesting thing that is pump storage hydro

power plants similar to co-generation power plant this power plant is also interesting. It is co-generation.

what is co-generation? power plant. co-generation power plants are nothing, but the thermal power plant, but it also produce some steam additional steam along with electricity. Similarly, the pump storage hydro power plant is nothing, but a hydro power plant with some additional features. Now, please try to understand what happens the water is being discharged through a plant that produce electricity, but it may so happen once you discharge those water they normally flow and, but few natural storage systems we can see the water is being stored at a lower level chamber where actually the water which has been produced by the hydro power plant is not completely discharged or flow to a different agriculture lands or rural areas, but it may happen that part of the water can be stored before it is completely discharged. Now, the question here the question here the water is actually freely available to me there is no cost to my water am I right all right. So, that is why the energy cost from a hydro power plant is much cheaper and the cheapest compared to any other energy sources. So, this is cheaper as well as cleaner all right. So, now, because this water is free to me. So, it is because we get it naturally to rain or you know the ice melting, but now if I can take the water which has been discharged from a power plant back to my dam and generate electricity it is recycled basically if I can do it is wonderful, but to get the water back I must need electricity you know to pump the water back. So, what has happened I have generated and then electricity is being generated and the same electricity is being used to generate the water back to the dam and because of efficiency issue it is not a good idea you know the amount of electricity that you have generated in a very ideal case if x amount of water being discharged and you like to carry those x amount of water back to the dam then probably the amount of electricity that you generated is not enough to take it back because of losses and efficiency. So, but there is one interesting point the cost of electricity in a day is keep on varying and during off peak hours that is midnight the cost of electricity may be one unit or unit number one or rupees one for example, but during peak hours 7 p.m. the cost of energy is as high as five units or five rupees. So, the suggestion here or what the experts utilize the pumped storage hydropower plant that they can take the water back when the energy is cheaper and discharge the water when the energy is costlier. So, during the energy cost being equal to rupees one I can take the water back and discharge when the energy cost is rupees five. So, even though the efficiency I may lose bit of percentage of energy, but the five six fold of energy requirement during peak hours can be met. So, pumped storage hydropower plant is a wonderful way of storing energy by taking the water back to your power plant and discharge as and when required.

So, for a battery we do the same thing whenever there is excess energy available to me I store it and whenever it is needed actually I discharge it. So, hydropower plant is to me a

wonderful storage mechanism and we need to explore this operation and it is a very very interesting and important one for all of us. Now, looking back to renewable energy growth and renewable energy growth across the world is keep on increasing there is no doubt about it, but especially country like ours for last one decade the renewable energy sources power share has significantly increased probably it may be due to government push or maybe it is a time at this point of time we are very keen to go for clean energy and hence renewable what would be the reason, but at the end of the day the conclusion is we are crazy towards huge installation of renewable energy sources. This should perhaps reduce the global warming we expect. However, it will not be easy with the renewable to economically disperse the thermal power plants due to their naturally natural intermittency.

Now, the question is you know when we had only thermal power plants I knew that x tons of coal is available to me I can produce y megawatt of power and I know my consumers and I keep on producing, but today because of renewable energy I have to reduce the generation from my conventional sources such as thermal power plants, but the question is because the renewable energies keep on oscillating it is intermittent in nature and you cannot expect renewable power to be produced in a constant magnitude because the wind may be there may not be there sun may be there sun may not be there. So, the generation output due to the installation of renewable energy is an uncertainty associated with that and hence it is keep on varying and because I do not know how much power I am going to get out of renewable energy installations and hence the power requirement from the thermal power generation is also not known to me. So, once I do not know how much power need to be generated from a thermal power plant it is very difficult for me to optimize the generation mix of many thermal power plants to meet the required power. So, that is one challenge I expect everyone to address and it is a very interesting problem. However, the convert converters associated with the renewable would decrease the overall inertia of the system too. There is one more challenge thermal power carry too much of inertia. I like to make you understand here that whenever there is a variation in my load anytime because we keep on switching on the air conditioner we keep on switching on the heaters we switch on and off as we wish. But no time I have been told that please wait for couple of seconds to get the power no. So, who is managing that because thermal power plants are you know mechanical systems if I have to increase the power output then I have to do certain processes and to do that I have to waste at least few seconds to get the power. But as an individual I have no patience to switch on my TV and wait for couple of seconds to watch. No, the moment I switch on I want the TV to be switched on. So, who helps me to do that and it is happening today. This is because those huge generators do carry inertia within it. That means they do store some energy within themselves as and when there is an oscillation of requirement they provide that inertial power. And hence we do not realize any mismatch between my requirement and its

availability.

But whereas in case of renewable energy wind for some extent it is fine but especially solar there is no rotational part. If you do not have rotational part then you do not have inertial energy or power. And because of which there is lot of challenge so if you put lot of solar power plants in any power grid then probably you are reducing your inertia energy and which is not good. So, to my understanding we can certainly increase our renewable energy but we cannot completely get rid of rotational energy systems such as thermal or hydro. We need to have some of them to support my renewable energy. So, we have identified that there are two major challenges. One, the renewable energy which is not fixed which is intermittent in nature and also it fail to accumulate huge inertial energy which also will be a challenge for thermal power plants to take a call. The amount of energy generation that they have to produce at a given point of time. Now, let us also try to understand different renewable energy technologies to start with actually let us focus on photovoltaics. And as you all know that this is one of the most prominent energy sources across the world and specific to India we are dependent on solar energy.

And due to the photovoltaic effects as you know the electricity is produced and silicon is usually used as semiconductor. It is simple, no noise, no rotating device, easily portable to carry. Now, multiple solar cells in an integrated group form photovoltaic panel or a module as you could see that there are different layers are being created and some of them are connected in series, some of them are connected in parallel. There is one major issue with solar cells is that the efficiency. Researchers across the globe are working very hard to increase the efficiency and generally it is close to 20 percent as of today.

The applications seen in rooftop, solar parks, rural villages, street lights and also in electric vehicle charge. Now, the basic principle you can understand better from the right hand side diagram. The sunlight that falls in your silicon wafer and once it falls that the photon is observed and the electron gain energy and cause the band gap and move from valence band to the conduction band. Once that cycle is complete the electron hole pair is formed, the electron flows through the external circuit to produce electricity.

The rate of recombination decides the life of the material. So, let us now get into the electrical circuit diagram of a photovoltaic or PV equivalent circuit. Now, the left hand side very clearly says how a photovoltaic system being represented in the form of electrical networks and the right hand side graph very clearly talks about the I-V characteristic of the solar cells or this photovoltaic arrangements. Now, there are two things we need to focus here. One is as you could see the y axis and the x axis is representing your voltage and the y axis that represent your current as well as power. So, now, I can represent the whole relationship current versus voltage as well as power

versus voltage. Now, the current versus voltage characteristic is known as I-V characteristic and the power versus voltage is known as PV characteristic. The important part is to capture the maximum or efficient operating point from those two characteristics and once you are able to capture then you can produce maximum power out of it.

The current flow to the network is given as:

$I=I_0\left(e^{\frac{qV}{kT}}-1\right)$ ...1.3

$I=I_0\left(e^{\frac{qV}{nkT}}-1\right)$…1.4

Now, equation number 1.3 as well as 1.4 and the characteristics shown in figure 1.17 they are actually representing the mathematical equation in the form of the graph representation. Now, there are different type of photovoltaics today because of its efficiency. The first structure is monocrystalline is costlier which is quite popular is compared to polycrystalline. Now, monocrystalline is efficient as compared to polycrystalline. Early days we started with polycrystalline now we have moved to monocrystalline. The voltage output is higher in monocrystalline. The monocrystalline the temperature coefficient is lower as compared to polycrystalline. One pure silicon crystal arrangement is seen in monocrystalline as compared to polycrystalline. Now, similarly, we can also capture one more renewable energy source that is wind and try to understand the basic principle based on which the wind energy is being generated.

Now, wind turbines convert kinetic energy of wind to the mechanical energy. So, the turbines they rotate because of wind flow and through which electric energy is being produced. So, there is a machine the nature of machine we will talk in a due course of time. Now, wind energy is indirect form of solar energy ok. So, it basically there it falls and create energy here actually it rotates the nature rotates the wind turbines and then you get electricity. Even 1 percent of effective wind energy utilization can satisfy the global power demand. So, what does it mean? It says that we have such a huge potential with wind energy even with little utilization we can survive the whole world can survive. So, I think let us explore it, but there are bit of challenges that we will discuss in due course of time. The wind the maximum wind availability is not on offshore I mean onshore, but it is maximum is available in the offshore. So, the technology required to take this wind plant into the sea and having a transformer and the cabling to get the electricity to the onshore become a challenge and we will tell you bit of that.

Nowadays wind turbines of megawatt capacity are seen everywhere feeding power to the grid. Initially, it was in kilowatt level and today it is in megawatt scale. So, 2, 5, 10

megawatt become the commonly seen wind turbines today in field. Now, if you see the types of wind energy there are different type of technologies that helps you to understand how wind can be converted into energy. One is known as very importantly horizontal axis. The axis of up rotation is parallel to the ground. The second is actually vertical axis. The axis of up rotation is perpendicular to the ground and most of the modern day wind turbines belong to the horizontal axis type as it is more efficient. Now, when it produce wind energy aerodynamic modeling equation of the wind turbine is given by:

$$P_m = C_p(\lambda, \beta)\frac{\rho A}{2}V_{wind}^3 \ldots 1.5$$

Where, C_p is known as the power coefficient,

ρ is the air density in kg/m^3,

A is the turbine swept area,

V_{wind} is the wind speed upstream in m/s and

β is the blade Pitch angle.

λ which is known as the tip speed ratio given by:

$$\lambda = \frac{R\omega}{V_{wind}} \ldots 1.6$$

Now, the mathematical analysis and nonlinear model that describes the given relation.

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\beta^x - C_5\right)e^{\frac{-C_6}{\beta}} \ldots 1.7$$

Where, C_P (λ, β) depends on the wind turbine rotor type. The power coefficient is unique for each wind turbine because the nature of wind, the construction, the design that decides your power coefficients. The power coefficient is often identified through empirical means. There is no standard formula and it need to be obtained.

The total, the typical coefficient values are 0.5, 160, 0.40, 0.51 and so and so. The parameter $\frac{1}{\lambda_i}$ is given by:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \ldots 1.8$$

Now, when you see the wind energy of any turbine, the turbine power you know they keep on varying depending upon your wind speed and both the diagrams typically tells you the turbine speed versus the power. So, if the speed is keep on changing, the power is also going on keep on changing. With different pitch angle settings, you can also see the

power output is keep on varying. I hope you understand what is pitch angle that means the blades know they can you know flip in different directions and if they flip in different directions, then the power reduced will also keep on changing.

Now, there is one interesting similar to our thermal generators I told you that we need to be very careful about operating point which is between P_{min} and P_{max}. So, similarly in wind energy also based on the speed, we need to understand at what maximum speed a wind turbine can rotate. Now, you may be thinking if the wind speed is maximum, then the power production is also maximum which is not true because when the wind speed is maximum probably till it like a cyclone. So, you cannot have maximum power during a cyclone.

So, there are few variables that we need to understand. The first one is cut-in speed. So, this is the minimum speed by which the wind turbine start producing power. So, first of all it start rotating, but it is not necessary to produce power and after some time you know when it picks up the reasonable speed, then only it start producing power and then you have a cut out speed. This is the maximum wind speed by which the wind turbine would stop producing the power. So, beyond a particular speed I think it is not good for the wind turbine to rotate. So, probably it stop and that is known as cut up speed. Now, what is rated speed? This is the speed at which the maximum power is obtained. So, what happens the power output versus speed at a plot with respect to speed actually keep on increasing and then it becomes saturated and then start dropping. So, we need to capture that speed at which maximum power is being produced from a wind power. Now, wind energy conversion system which is typically the way it happens first of all wind which applies to my wind turbine rotor and then there is a gear box and then that rotate my wind turbine generator and then we do have power electronic converters for converting energy from one form to other and then it is connected to my utility gear. Now, there are different type of actually wind turbines and you could see there are four diagrams A, B, C, D and they are typical arrangements to which wind turbines operate.

The first type is known as fixed speed wind turbine which is known as type 1 and then the second one which is variable slip wind turbine which is type 2 and the third one is very very popular and commercially being utilized across the world and that is DFIG. So, double fed induction generator wind turbine which is type 3 and then fourth one is full converter wind turbine which is type 4. So, depending upon the technology any kind of configurations are acceptable, but most popular today type 3 which is very commonly used, but other technologies are still in model. Now, there is one important variable that we need to understand or a concept which is known as Bertz limit.

This gives the theoretical highest possible efficiency of the wind turbine. Now, what we

understand if you have a wind turbine that how to increase the efficiency what would be the speed where maximum power can be produced, what would be the architecture, what would be the technology so that you know the maximum energy can be produced similar to my solar. So, it is supposed to be 59.3 percent maximum efficiency that means we cannot go beyond 59 percent that is what it has been told and the practical efficiency would fall in the range of 35 to 40 percent. So, if you compare with solar and wind that is close to 20 percent and this is close to 40 percent. So, being the double the efficiency wind turbines or wind generators being a renewable energy source is being preferred compared to solar, but there are structural challenges, resource available challenges, but preferably given a choice wind versus solar most of the people prefer to go for wind, but if you are not a country having good wind flow or the sources are not available to you and if you are not a sunny country then probably solar could be preferred.

Now, how do you extract maximum power from a wind generator? There are different technology through which you can extract maximum power. The first important is pitch angle control. So, the angle of attack is varied in the case of pitch angle of control. So, you can try to control the pitch angle to extract the maximum power and the most effective means of limiting power during higher wind speeds.

So, when there is high wind speed probably we can control the pitch to extract the maximum power. Then one more control mechanism is known as rotor speed control. This is used if small variation in the power is considered. So, if you consider the small variation in power probably that can be managed through rotor speed control and then you have a yaw control ensure that the turbine is export the wind to maximum power and refers to rotation of wind turbine in the horizontal axis. Now, let us try to understand the technology and the challenges with onshore and offshore.

As you all know onshore wind farms are very easy to install and they are located on the land. The onshore wind plants can be seen in India in many places especially the coastal India that is Tamil Nadu, Karnataka and Gujarat. The onshore wind is the one which flow from sea towards the land. So, when there is a wind flow from the sea towards the land so probably that is the location where such onshore wind turbines can be installed. And it is certainly cheaper compared to offshore technology because you can easily put a substation near to that, you can extract the power and you can also integrate with the distribution system. However, in case of offshore or the technology, the transmission of power, the underground cabling within the sea become a challenge.

The maintenance cost of onshore is also very minimum and studies suggest this type affects the life of birds and other animals. I think there is an issue where some of the NGOs they are a bit concerned because the blade is keep on moving so it may also hurt

many wonderful birds and wildlife actually activities that happen in a particular journey. Now, let us focus on offshore and offshore means you get into the sea and then establish your wind farms and they are located within the sea and the wind is blown from the land to the ocean it is opposite. So, it is going from the land to the ocean so that case we can go for offshore. This is more efficient as compared to onshore and there is the reason being there is no disturbance of human activities and they indirectly tend to protect the marine ecosystem, because they are not good to hurt anybody.

So, because the marine ecosystem is still protected and the HVDC cabling is used high voltage DC cabling to extract the power to the onshore. Now, there is one more interesting challenge about the wake effect. What happens when we install wind power plants you cannot do one or two there is a power one after other it is getting connected. So, when you cut the speed that speed actually because disturb the whole environment and probably the speed available the wind speed available to the next parallel or adjacent wind turbine will be affected, okay. So, the wake effect is nothing you can see from the diagram many wind power plants are covered with the the kind of wind flow being disturbed by one of the power plants. So, the wake effect is nothing but the turbulence caused due to obstacle of the wind from the first row of wind turbines. So, if you have n number of wind turbines in different rows the first wind turbine will disturb the second, second will disturb the third. So, the wind speed which is available to the first one smoothly is not available to the second one because it disturbs and create a turbulence around it and hence there is a reasonable distance being maintained, but still the wake effect cannot be ignored. Significant power drop is seen and close to 10 to 20 percent with other power plants because of this turbulence effect. At least 10D distance is maintained between the rows. So, you know there is a standard structure through which huge distance is maintained so that the turbulence effect will be nullified, but still you cannot completely avoid it. Jensen modeling is used to consider the wake effects. So, depending upon the flow for air and wind probably you can plan and place them in such a manner so that the wake effect is minimized. Now, moving to the last very important section of your energy storage technology which is the battery technology. You all know that you know renewable energy which is available to me not throughout the day and unfortunately I am keep on mentioning and I am repeating it today that God happened to be not very kind to engineers and what the God has done basically, he given him free energy, go through solar and wind, but they are available to you at a point of time when you really do not need energy because the solar energy is available to me during lunch hours when we are not really working and also the wind energy is available to me during midnight where most of us are sleeping. We need energy, but not the peak energy requirement. So, the peak energy requirement is an evening let us say 7 p.m. and you do not have wind neither you have actually sun. So, it is important for me to store those enough energy available to me through renewable and discharge them during peak hours

and to do that you need storage and those storages are not small batteries, but they are huge energy storage devices and there are different type of storage technologies, mechanical energy storages, chemical energy storages, biological energy storages, magnetic energy storages, thermal energy storages as well as thermo chemical energy storages. Now, if you see the whole set of diagrams the battery energy storage systems are divided into two sections one is known as primary, the other one is secondary and the primary they could be the lithium or alkaline and in case of secondary it could be lead acid, nickel based, lithium ion, MAS, metal ion, flow battery and all those technologies.

So, today we are very keen to use the secondary batteries for large renewable energy storage technologies. Now, one thing is very important lithium ion is considered to be one of the best storage technology as of now and the cost was an issue, but fortunately the cost is keep on dropping over a period of time. Now, after understanding different type of energy generation resources or the technologies thermal, hydro, nuclear, solar, wind, energy storage devices now we are moving to the real the course title is that is on economic dispatch. So, before we start this we need to understand what is economic dispatch. Now, first of all let us understand the whole energy requirement of a ecosystem or a network energy system energy ecosystem is not being met by one or two generators, but it is met by hundreds and thousands of generators. Now, the question is when there are 100 generators need to meet your required demand we need to also understand how much each individual has to dispatch. So, that the overall cost that we need to spend to meet my required load is minimum and that process is known as economic dispatch. Means how efficiently, optimally and economically each generator has to generate so that the required demand is being met by all my generators efficiently, effectively and with minimum cost. And the main objective of economic dispatch is to achieve minimum operating cost, it should also include environmental concerns and to include system constraints to ensure security of the network thereby avoiding the collapse of the whole network. Now, when you have networks, each and every corridor (transmission corridor) has certain limit to their power gaining capabilities. Now, if you have a generator connected to a network means this is my generator and probably that is connected to two transmission line to a load. So, now the question is if I keep on increasing its generator to make it is economical, but if this transmission corridor is not capable of carrying this imagine the capacity is 100 MVA and if I like to produce 120 MVA of power certainly we cannot carry it. So, there is a violation of security. So, the network must be in a position to dispatch your requirements. So, optimization means you decided how much they have to generate, but also you need to see those optimal generations can it be dispatchable whether the network is supporting me to carry that is an important thing. Now, one more important point that just environmental concern I forgot to mention prior to this where when you generate especially the thermal power plants they also pollute the environment.

One thing is very clear your power generation is also directly proportional to the environmental pollution. So, you need to also understand that up to what extent I should optimize my generation not to disturb the environmental constraints. So, there are few challenges first you have to optimize your generation output agree, but also make sure that you know the cost is minimum the environmental constraints are being satisfied the security constraint of the network is being satisfied and also it can sink with other generating resources like hydrothermal coordination also being not disturbed. Now, there is one more important part that when you optimize your generation and also able to cater the customers without violating transmission constraint and that process is known as actually optimal power flow technique. Optimal economic dispatch satisfying power flow constraint together is known as optimal power flow. Now, there is one more interesting concept is known as unit commitment though we will be discussing in detail in due course of time. Now, in case of unit commitment if you have n number of generators one thing that you switch on all the generators and extract the optimal operating point so that it is economical. The other option could be when you have n number of generating units it is not necessary that I have to make all the generators operational at all the time means there are 2 to power n minus 1 combination of generators on and off status is possible. So, we can identify that how many of those units need to be switched on and those switched on units has to dispatch economically. So, that is known as unit commitment problem we will discuss in detail over a good time. Now, considering the maintenance of the plant not overloading the system element that is transmission lines, transformers, scheduling the real and reactive power sources establishing the good tap positions of the transformers.

So, these are all can be included as a constraint to my optimal power flow operations. In this part as you can see that India's top renewable energy projects including world's largest solar power as you could see this in Indian graph it very clearly says that the locations where majority of the important projects are currently going on and I request all of you to Google and try to understand the geography and the different projects on renewable are currently in progress that will really motivate you more to enjoy the subjects. So, with this note, I mean, I appreciate all of you to go through the following references to understand more about and more details because due to limitation of time. So, probably I might not have touched some of the portions which we need to be given special attention. So, I request all my dear students to get into those books and try to understand more about the concepts that I have clarified in today's lecture. Thank you.